

# Search for neutrinoless double beta decay with the NEMO-3 detector: first results

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The NEMO-3 detector, which has been operating in the Fréjus Underground Laboratory since February 2003, is devoted to searching for neutrinoless double beta decay ( $\beta\beta 0\nu$ ). The expected performance of the detector has been successfully achieved. Half-lives of the two neutrinos double beta decay ( $\beta\beta 2\nu$ ) have been measured for  $^{100}\text{Mo}$ ,  $^{82}\text{Se}$ ,  $^{96}\text{Zr}$ ,  $^{116}\text{Cd}$  and  $^{150}\text{Nd}$ . After 265 days of data collection from February 2003 until March 2004, no evidence for neutrinoless double beta decay ( $\beta\beta 0\nu$ ) was found from  $\sim 7$  kg of  $^{100}\text{Mo}$  and  $\sim 1$  kg of  $^{82}\text{Se}$ . The corresponding lower limits for the half-lives are  $3.5 \times 10^{23}$  years at 90% C.L for  $^{100}\text{Mo}$  and  $1.9 \times 10^{23}$  years for  $^{82}\text{Se}$ . Limits for the effective Majorana neutrino mass are  $\langle m_\nu \rangle < 0.7 - 1.2$  eV for  $^{100}\text{Mo}$  and  $\langle m_\nu \rangle < 1.3 - 3.2$  eV for  $^{82}\text{Se}$ . Radon is the dominant background today and a Radon-free purification system will be in operation by the end of september 2004. The NEMO-3 expected sensitivity after 5 years of data is 0.2 eV.

## 1. Introduction

Neutrinoless double beta decay ( $\beta\beta 0\nu$ ) is a process beyond the Standard Model which violates lepton number by 2 units. The discovery of this decay would be experimental proof that the neutrino is a Majorana particle. It would also constrain the mass spectrum and the absolute mass of the neutrinos. The NEMO-3 detector is devoted to searching for  $\beta\beta 0\nu$  decay with the direct detection of the two electrons from  $\beta\beta$  decay by a combination of a tracking device and a calorimeter.

## 2. The NEMO-3 detector

The NEMO-3 detector [1], installed in the Fréjus Underground Laboratory (LSM, France) is a cylinder divided into 20 equal sectors. The isotopes present inside the detector in the form of very thin foils ( $30\text{-}60$   $\text{mg}/\text{cm}^2$ ) are  $^{100}\text{Mo}$  (6914 g),  $^{82}\text{Se}$  (932 g),  $^{116}\text{Cd}$  (405 g),  $^{130}\text{Te}$  (454 g), natural Te (491 g),  $^{150}\text{Nd}$  (34 g),  $^{96}\text{Zr}$  (9 g),  $^{48}\text{Ca}$  (7 g) and Cu (621 g). Natural Te and Cu are devoted to measuring the external background. The sources have been purified to reduce their content of  $^{214}\text{Bi}$  and  $^{208}\text{Tl}$ . On both sides of the sources, there is a gaseous tracking detec-

tor. It consists of 6180 open drift cells operating in the Geiger mode regime (geiger cells) which gives three-dimensional track reconstruction. To minimize the multiple scattering, the gas is a mixture of 95% He, 4% ethyl alcohol and 1% Argon. The wire chamber is surrounded by a calorimeter which consists of 1946 plastic scintillator blocks coupled to very low radioactive photomultipliers (PMTs) especially developed by Hamamatsu. A solenoid surrounding the detector produces a 25 G magnetic field in order to recognize electrons and distinguish them from positrons. Finally an external shield of 18 cm of low radioactivity iron covers the detector to reduce external  $\gamma$  and thermal neutrons. Outside the iron, a water shield and a wood shield thermalize neutrons. Thus the combination of a tracking detector, a calorimeter and a magnetic field allows the identification of electrons, positrons,  $\gamma$  and  $\alpha$  particles.

## 3. Performance of the detector

Within the tracking detector, 99.5% of the geiger cells are functioning normally. The vertex resolution in the 2 electron channel has been measured using the simultaneous 2 electron conversion of  $^{207}\text{Bi}$  sources placed inside the detec-

tor. The resolution on the distance between the two reconstructed tracks is  $\sigma_t = 0.6$  cm in the transverse plane and  $\sigma_l = 1.3$  cm in the longitudinal plane. The ambiguity between  $e^-$  and  $e^+$  is 3% at 1 MeV.

Within the calorimeter, 97% of the PMTs coupled to scintillators are functioning correctly. The energy resolution, measured every  $\sim 40$  days using  $^{207}\text{Bi}$  sources, is 15% (FWHM) at 1 MeV for the 5" PMTs on the external wall and 17% for the 3" PMTs on the internal wall. A daily laser survey controls the gain stability of each PMT. The efficiency to detect a  $\gamma$  at 500 keV is about 50% with a threshold of 30 keV. The time resolution measured with the 2 electron channel, is 250 ps at 1 MeV which is much smaller than the time-of-flight of a crossing electron that is larger than 3 ns. Thus external crossing electrons are totally rejected.

In conclusion, the expected performance of the NEMO-3 detector has been successfully achieved.

#### 4. Measurement of $\beta\beta 2\nu$ decays with several nuclei

The detector has been running since February 2003. The trigger configuration requires at least 1 PMT with an energy above 150 keV and 3 active geiger cells. The trigger rate is  $\sim 7$  Hz. A  $\beta\beta$  event is an event with 2 tracks coming from the same vertex on the foil. Each track is associated to a fired scintillator with a good internal time-of-flight hypothesis, and the curvature corresponds to a negative charge. Such a  $\beta\beta$  event is detected every  $\sim 1.5$  minutes. After 241 days of data analysed, more than 140,000  $\beta\beta 2\nu$  events from  $\sim 7$  kg of  $^{100}\text{Mo}$  have been measured. Figure 1 shows the spectrum of the summed energy of the two electrons for  $^{100}\text{Mo}$  after background subtraction which is in agreement with the expected spectrum from  $\beta\beta 2\nu$  simulation.

The subtracted background is very low, corresponding to a very high signal-to-background ratio of 46. The preliminary value of the measured half-life is  $7.72 \pm 0.02(\text{stat}) \pm 0.54(\text{syst}) 10^{18}$  y. The  $\beta\beta 2\nu$  decay has also been measured for  $^{82}\text{Se}$ ,  $^{96}\text{Zr}$ ,  $^{116}\text{Cd}$  and  $^{150}\text{Nd}$ . Preliminary results are summarized in table 1.

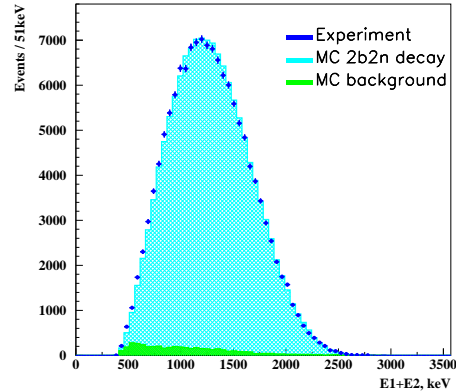


Figure 1. Spectrum of the energy sum of the two electrons from 6.914 kg of  $^{100}\text{Mo}$  after 241 days of data collection.

#### 5. Study of the background in the $\beta\beta 0\nu$ energy window

After almost 1 year of data, the level of each component of the background has been directly measured using different channels in the data.

External  $^{214}\text{Bi}$  and  $^{208}\text{Tl}$  backgrounds (mostly inside the PMTs) have been measured by searching for external ( $e^-, \gamma$ ) events in the data. The total reconstructed activity of  $^{208}\text{Tl}$  is  $\sim 40$  Bq and is in agreement with previous HPGe measurements of a sample of the PMTs glass. The expected number of  $\beta\beta 0\nu$ -like events is negligible,  $\lesssim 10^{-3}$  counts  $\text{kg}^{-1}\text{y}^{-1}$  in the  $[2.8-3.2]$  MeV energy window where  $\beta\beta 0\nu$  signal is expected.

External neutrons and high energy  $\gamma$  backgrounds have been measured by searching for internal ( $e^-, e^-$ ) events above 4 MeV. Only 2 events have been observed in 265 days of data collection, as expected in the Monte-Carlo.

Table 1  
Preliminary results of the measurements of  $\beta\beta 2\nu$  decays

Isotope	mass (g)	days of data	number of $\beta\beta$ events	Signal/ Background	$T_{1/2}(\beta\beta 2\nu)$ (years)
$^{82}\text{Se}$	932	241.5	2385	3.3	$10.3 \pm 0.2(stat) \pm 1.0(syst)10^{19}$ y.
$^{96}\text{Zr}$	9.4	168.4	72	0.9	$2.0 \pm 0.3(stat) \pm 0.2(syst)10^{19}$ y.
$^{100}\text{Mo}$	6914	241.5	145245	45.8	$7.72 \pm 0.02(stat) \pm 0.54(syst)10^{18}$ y.
$^{116}\text{Cd}$	405	168.4	1371	7.5	$2.8 \pm 0.1(stat) \pm 0.3(syst)10^{19}$ y.
$^{150}\text{Nd}$	37.0	168.4	449	2.8	$9.7 \pm 0.7(stat) \pm 1.0(syst)10^{18}$ y.

This background is also negligible,  $\lesssim 0.02$  counts  $\text{kg}^{-1}\text{y}^{-1}$  in the  $[2.8 - 3.2]$  MeV  $\beta\beta 0\nu$  energy window.

The level of  $^{208}\text{Tl}$  impurities inside the molybdenum sources has been measured by searching for internal ( $e^-, \gamma$ ) and ( $e^-, \gamma\gamma$ ) events. An activity of  $\sim 100 \mu\text{Bq/kg}$  has been measured in good agreement with the previous Ge measurements done before installing the sources in the detector. This corresponds to an expected number of  $\beta\beta 0\nu$ -like events of  $\sim 0.1$  counts  $\text{kg}^{-1}\text{y}^{-1}$  in the  $[2.8 - 3.2]$  MeV  $\beta\beta 0\nu$  energy window.

The expected level of background due to the tail of the  $\beta\beta 2\nu$  is  $\sim 0.3$  counts  $\text{kg}^{-1}\text{y}^{-1}$  in the  $[2.8 - 3.2]$  MeV  $\beta\beta 0\nu$  energy window.

The dominant background today is the radon inside the tracking chamber due to a low level of diffusion of the radon inside the laboratory ( $\sim 15 \text{ Bq/m}^3$ ) into the detector. Two independent measurements have been carried out. A high efficiency radon detector has measured radon in the NEMO-3 gas. Radon can also be measured directly by searching for ( $e^-, \alpha$ ) events in the NEMO-3 data. Indeed the tracking detector allows the detection of the delayed tracks (up to  $700 \mu\text{s}$ ) in order to tag delayed alphas emitted by  $^{214}\text{Po}$  in the  $Bi - Po$  process. Both measurements are in good agreement and indicate a level of radon inside the detector of  $\sim 20\text{-}30 \text{ mBq/m}^3$ . This radon contamination corresponds to an expected number of  $\beta\beta 0\nu$ -like events of  $\sim 1$  count  $\text{kg}^{-1}\text{y}^{-1}$  in the  $[2.8 - 3.2]$  MeV  $\beta\beta 0\nu$  energy window, a factor  $\sim 10$  too high to reach the expected sensitivity. A Radon-free purification system, designed to reduce radon contamination by a factor

$\sim 100$  will be in operation by the end of September 2004.

## 6. Preliminary results on the limit of $\beta\beta 0\nu$ decay with $^{100}\text{Mo}$ and $^{82}\text{Se}$

Figures 2 and 3 show the spectrum of the energy sum of the two electrons in the  $\beta\beta 0\nu$  energy window after 265 days of data collection with 6.914 kg of  $^{100}\text{Mo}$  and 0.932 kg of  $^{82}\text{Se}$  respectively.

The number of two electron events observed in the data is in agreement with the expected number of events from  $\beta\beta 2\nu$  and the radon simulations.

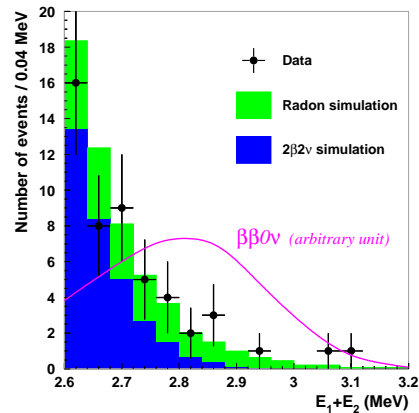


Figure 2. Spectrum of the energy sum of the two electrons above 2.6 MeV from 6.914 kg of  $^{100}\text{Mo}$  after 265 days of data collection.

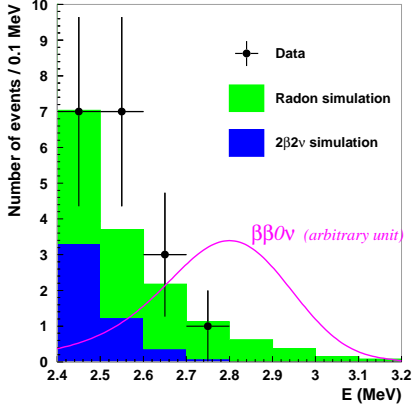


Figure 3. Spectrum of the energy sum of the two electrons above 2.4 MeV from 0.932 kg of  $^{82}\text{Se}$  after 265 days of data collection.

In the energy window  $[2.8 - 3.2]$  MeV, the expected background is  $7.0 \pm 1.7$  and 8 events have been observed from  $^{100}\text{Mo}$ . To check independently the dominant radon contribution above 2.8 MeV, the same energy sum spectrum (Fig. 4) has been plotted for the two electrons emitted from the copper and tellurium foils where no background except radon is expected: the data are in agreement with the radon simulation.

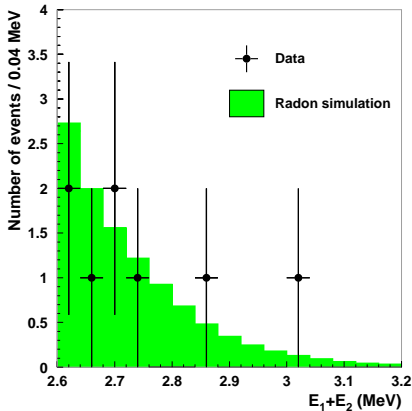


Figure 4. Spectrum of the energy sum of the two electrons above 2.6 MeV from copper and tellurium foils after 265 days of data collection.

The NEMO-3 detector is able to measure not only the energy sum ( $E_{tot}$ ) of the  $2e^-$  events but also the single energy ( $E_{min}$  energy of the  $e^-$  of minimum energy) and the angle between the two tracks ( $\cos\theta$ ). Moreover the level of each component of background can be measured through studies of different channels, as explained above. Therefore a maximum likelihood analysis has been applied on  $2e^-$  events above 2 MeV using these three variables [2]. A three-dimensional probability distribution function,  $P^{3D}$ , can be written as:

$$P^{3D} = P(E_{tot}) P(E_{min}/E_{tot}) P(\cos\theta/E_{min})$$

where  $P(E_{min}/E_{tot})$  and  $P(\cos\theta/E_{min})$  are two conditional probability distribution functions. The likelihood is defined as

$$\mathcal{L} = \prod_{i=1}^{N_{tot}} \left( \sum_{k=1}^8 x_k P_{3D}^k \right)$$

where  $k$  corresponds to one of the 8 contributions:  $\beta\beta 0\nu$ ,  $\beta\beta 2\nu$ , Radon, external and internal  $^{214}\text{Bi}$  and  $^{208}\text{Tl}$ , and neutrons.  $x_k$  is the ratio of the number of  $2e^-$  events due to the process  $k$  to the total number of observed events  $N_{tot}$ ,  $P_{3D}^k$  is built using simulated events of the contribution  $k$ . The only free parameter is  $x_{0\nu}$ .

With 265 days of data, limits obtained with the likelihood analysis are  $T_{1/2}(0\nu) > 3.5 \times 10^{23}$  years at 90% C.L for  $^{100}\text{Mo}$  and  $1.9 \times 10^{23}$  years for  $^{82}\text{Se}$ . The corresponding upper limits for the effective Majorana neutrino mass range from 0.7 to 1.2 eV for  $^{100}\text{Mo}$  and 1.3 to 3.6 eV for  $^{82}\text{Se}$  depending on the nuclear matrix elements [3,4,5,6]. Limit on Majoron is  $T_{1/2}(M) > 1.4 \times 10^{22}$  years at 90% C.L, corresponding to a limit of  $\chi < (5.3 - 8.5) \times 10^{-5}$  [3,4].

## 7. Conclusions

The NEMO-3 detector has been running reliably since February 2003. The  $\beta\beta 2\nu$  decay has been measured for  $^{82}\text{Se}$ ,  $^{96}\text{Zr}$ ,  $^{100}\text{Mo}$ ,  $^{116}\text{Cd}$  and  $^{150}\text{Nd}$ . All components of the background in the  $\beta\beta 0\nu$  energy window have been measured directly using different channels in the data. The energy sum spectrum of  $2e^-$  events is in agreement with the simulations. After 265 days of data, no evidence for  $\beta\beta 0\nu$  decay is found from the 6.914 kg of  $^{100}\text{Mo}$  and 0.932 kg of  $^{82}\text{Se}$ . A likelihood analysis gives an upper limit for the effective neutrino

mass  $\langle m_\nu \rangle < 0.7 - 1.2$  eV for  $^{100}\text{Mo}$ . Radon is the dominant background today. A Radon-free purification system will be in operation by the end of September 2004. After radon purification and 5 years of data collection, the expected sensitivity will be  $T_{1/2}(0\nu) > 4 \times 10^{24}$  years at 90% C.L for  $^{100}\text{Mo}$  and  $8 \times 10^{23}$  years for  $^{82}\text{Se}$ , corresponding to  $\langle m_\nu \rangle < 0.2 - 0.35$  eV for  $^{100}\text{Mo}$  and  $\langle m_\nu \rangle < 0.65 - 1.8$  eV for  $^{82}\text{Se}$ .

## REFERENCES

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